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Technical Report

R 609

**CONDITIONED POWER SYSTEM USING A HIGH-SPEED
POWER SOURCE TRANSFER SWITCH**

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CONDITIONED POWER SYSTEM USING A HIGH-SPEED POWER SOURCE TRANSFER SWITCH

Technical Report R-609

YF 38.534.005.01.001

by

Aly A. Mahmoud and H. H. Kajihara

ABSTRACT

The reliable operation of critical electronic equipment employed at naval shore installations and other Department of Defense installations requires conditioned electrical power. A conditioned power system is proposed which is potentially one-fifth as costly as power systems employing solid-state or rotary uninterruptible power supplies. The proposed conditioned power system employs high-speed, solid-state power source switching. A 15-kva, 208-volt, 60-Hertz, 3-phase demonstration model of the proposed system has been developed and laboratory evaluated. This model accomplishes power source transfer in 800 μ sec. Because of its fast switching speed between two power sources, the system is potentially capable of conditioning power economically for many critical loads.

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INTRODUCTION

The reliable operation of critical electronic equipment employed at naval shore installations and other Department of Defense installations requires conditioned electrical power. Presently, to assure reliable, trouble-free operation of this electronic equipment, very expensive power conditioners, such as solid-state and rotary uninterruptible power supplies, are employed. These power supplies provide high quality power but are very costly. There is evidence that some critical equipment can tolerate power interruptions even of a few milliseconds duration.^{1,2} For these and other equipment that can withstand momentary power interruptions, a conditioned power system is proposed which is potentially one-fifth as costly as conditioned power systems employing uninterruptible power supplies. The proposed power conditioning system employs high-speed, solid-state power source switching.

This report describes a 15-kva, 208-volt, 60-Hertz, 3-phase demonstration model of the system now under development at NCEL. The model, which has been fully laboratory tested and evaluated, accomplishes power source transfer in less than 800 μ sec. Because of its fast switching speed between two power sources, the system is potentially capable of conditioning power for many critical loads.

EXISTING HIGH-QUALITY POWER SYSTEMS

There are several currently operational power conditioners by which precision quality power is supplied. One of these is a rotary uninterruptible power supply. A block diagram of this power supply is shown in Figure 1. It employs electrical machines and rotating mechanical components. The main disadvantages of this system are a periodic maintenance requirement and a high susceptibility to mechanical failures. Another basic system that has recently been made operational is a solid-state uninterruptible power supply. A block diagram of this power supply is shown in Figure 2. Both uninterruptible power supplies are expensive.

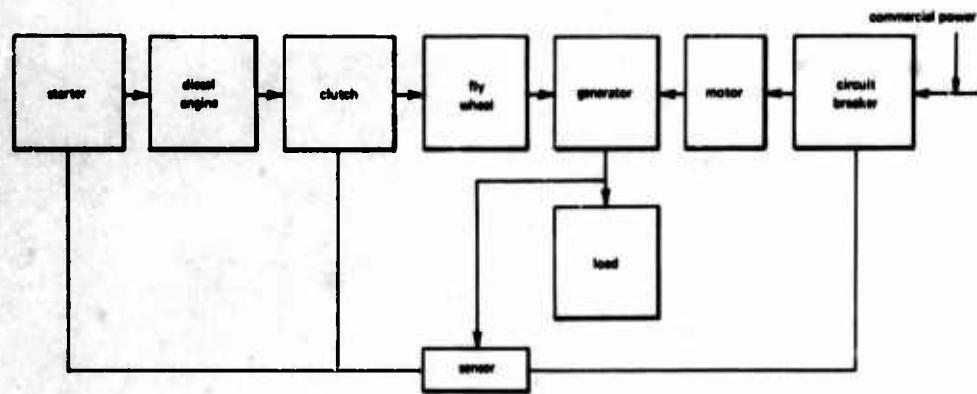


Figure 1. Block diagram of a typical rotary uninterruptible power supply.

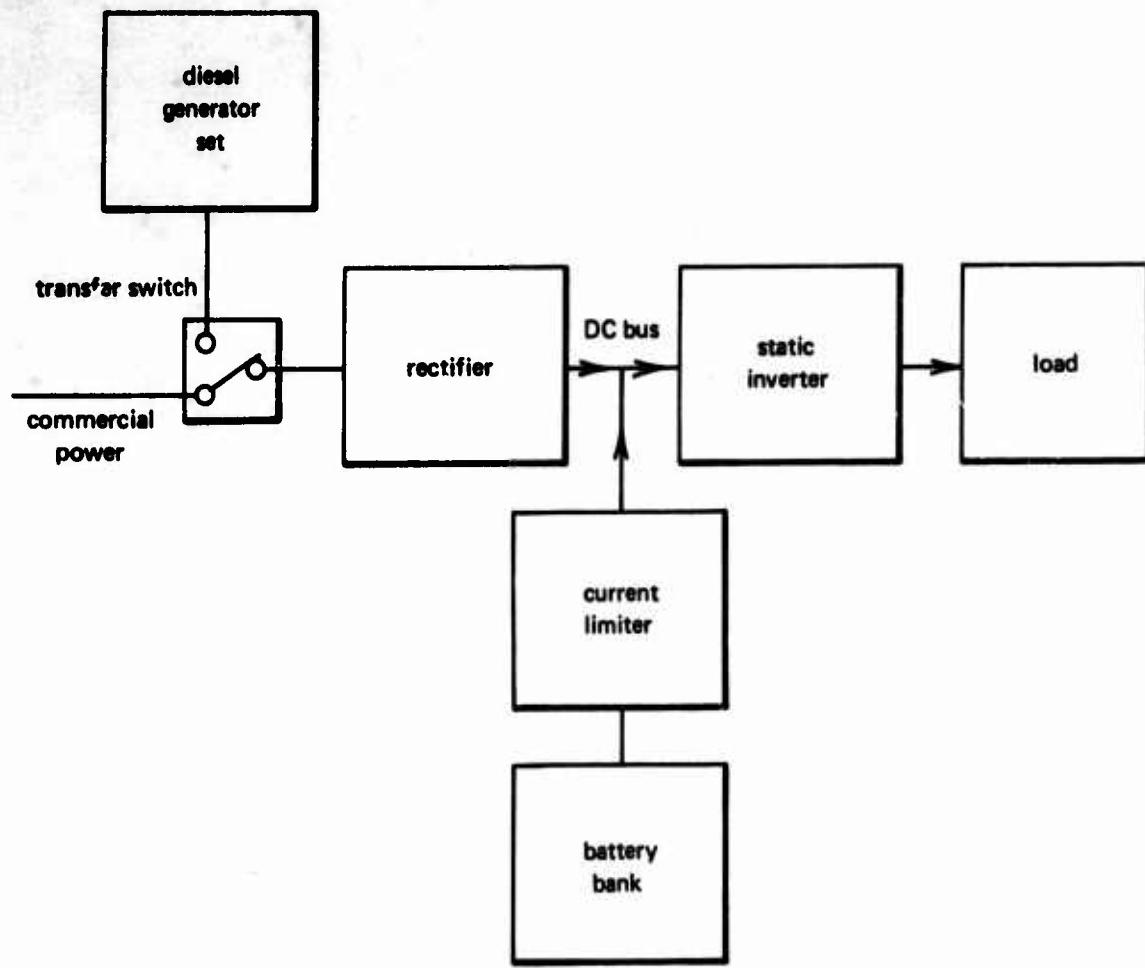


Figure 2. Block diagram of a typical solid-state uninterruptible power supply.

PROPOSED CONDITIONED POWER SYSTEM

The system under development at NCEL is a conditioned power system using high-speed power source transfer. In this system solid-state devices are utilized as high-speed static switches that transfer the critical load from one source to another. Therefore, if one source is interrupted, the system will transfer the load to the other source in such a way that the load experiences only a very short power discontinuity which does not disturb the operation of electronic equipment. The cost of the NCEL conditioned power system is considerably less than that of power systems employing either rotary or solid-state uninterruptible power supplies. It is estimated that a conditioned power system using high-speed switching will cost less than \$75/kw, as compared to \$450/kw and \$700/kw, respectively, for a rotary or a solid-state uninterruptible power supply.³

Conditioned power systems using high-speed power source transfer switching require the availability of two power sources. Two power sources are normally available in one of the following forms:

1. Two different utility companies, each supplying one power source. In this case, the two sources must be synchronized when transfer occurs so that the load voltage waveform is essentially continuous.
2. One utility company with two feeder lines. Since the two sources are supplied from the same power station, they are in phase and there is no synchronization problem.
3. One utility company and an on-site auxiliary or standby power supply. In such a case, the two sources must be synchronized during the transfer of load.

From the above discussion, it can be seen that in an ideal high-speed power source transfer, the switch should transfer the load from one source to the other regardless of the origin of the two sources. It should be able to transfer all types of loads in the shortest time possible and without creating any transients during the transfer. Furthermore, the cost should be much less than the rotary or solid-state uninterruptible power supplies.

The 15-kva, 208-volt, 60-Hertz, 3-phase demonstration model of the conditioned power high-speed, solid-state switching system is shown in Figure 3. It can transfer the critical load from the commercial source to the auxiliary source in 800 μ sec or less. The system detects a commercial source voltage drop exceeding 10% of normal voltage and switches the load to the auxiliary power source. When the commercial source returns to normal operation, the system will transfer the load to the commercial source.



Figure 3. Fifteen-kva solid-state conditioned power system.

A block diagram of the switching system is shown in Figure 4 and its circuit diagram is shown in Figure 5. The switching system consists of a pair of static switches between each of the power supply phases and the load. Each static switch contains two back-to-back silicon-controlled rectifier (SCR) switches. These switches are turned on by applying a train of positive pulses to the gates of the SCRs. The SCR triggering circuitry is shown in Figure 6. In order for the switches to be turned off, the current through the SCRs must be zero. Therefore, switchover from one supply source to another for a given phase always occurs at the time that the load current in the phase becomes zero. Because of the SCRs characteristics, it is necessary that both the auxiliary power supply and the commercial power supply be synchronized at the moment that transfer takes place; otherwise, a heavy circulating current will exist in the SCR's circuits that may damage

the devices, the critical load, and possibly the power sources. Synchronization of the two sources is also a necessity for a continuous voltage waveform to the load. An analytical treatment of the SCR operation is given in the Appendix.

The switching system presented here will transfer all three phases of the critical load from commercial source to auxiliary source almost immediately; however, the load is transferred back to the commercial source phase sequentially. Since the transfer from the auxiliary back to the commercial source occurs sequentially phase-by-phase, synchronization between the two power sources must be maintained for at least two-thirds of the cycle. To ensure that synchronization is maintained during the period of transfer, a logic circuit is incorporated in the system. This circuit also assures that transfer is accomplished for each phase as the load current reaches zero.

The voltage-sensing logic circuitry (detectors, blocking oscillator and buffer, flip-flops, synchronization generator, and gates) detects the voltage drop variation and determines if it is within the allowed limits. If the commercial source voltage is below or above the limits, the sensing circuit will trigger the transfer from the commercial to the auxiliary source. Whenever the commercial source is back to normal, it will be detected and the load will be transferred rapidly to the commercial source.

The circuitry consisting of the limiter discriminator and threshold detector measures the frequency of the commercial power and generates signals to control the logic circuits. Therefore, if the commercial frequency is above or below the specified 5%, the switch will transfer the load from the commercial source to the auxiliary source and back to the commercial source whenever the frequency is back to normal.

DESCRIPTION OF CIRCUITRY

Two main logic circuits are used in the present solid-state switching system. The voltage-sensing circuitry detects the drop in commercial line voltage, and if it is outside the specified range, it will trigger the SCRs of the auxiliary source while turning off the commercial SCRs thus transferring the load to the auxiliary power supply. When the commercial voltage is back to normal, the voltage-sensing circuitry will detect that and switch the load back to the commercial source.

The frequency-sensing circuit is designed to detect any frequency change exceeding 5% and, like the voltage-sensing circuitry, will transfer the load back and forth.

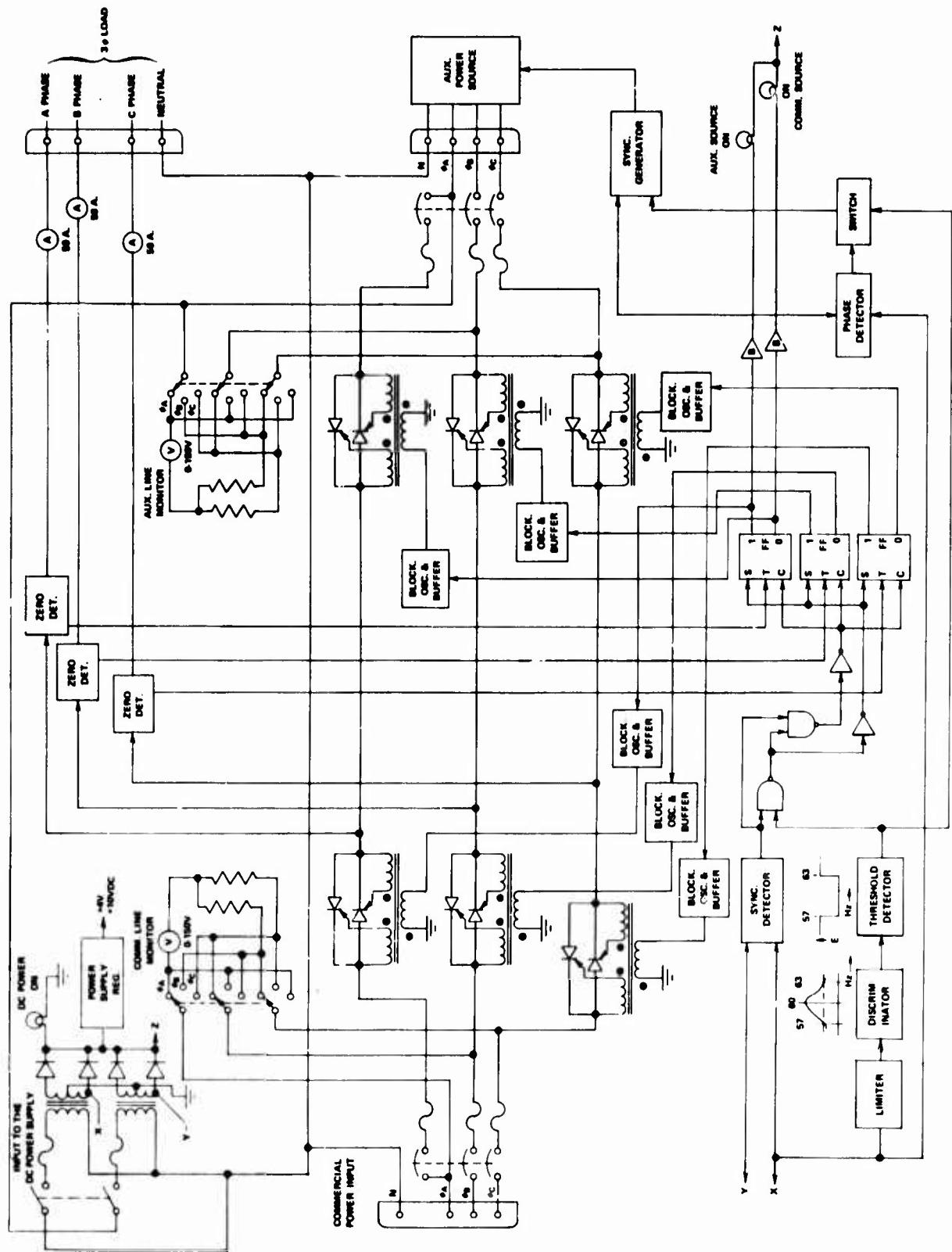
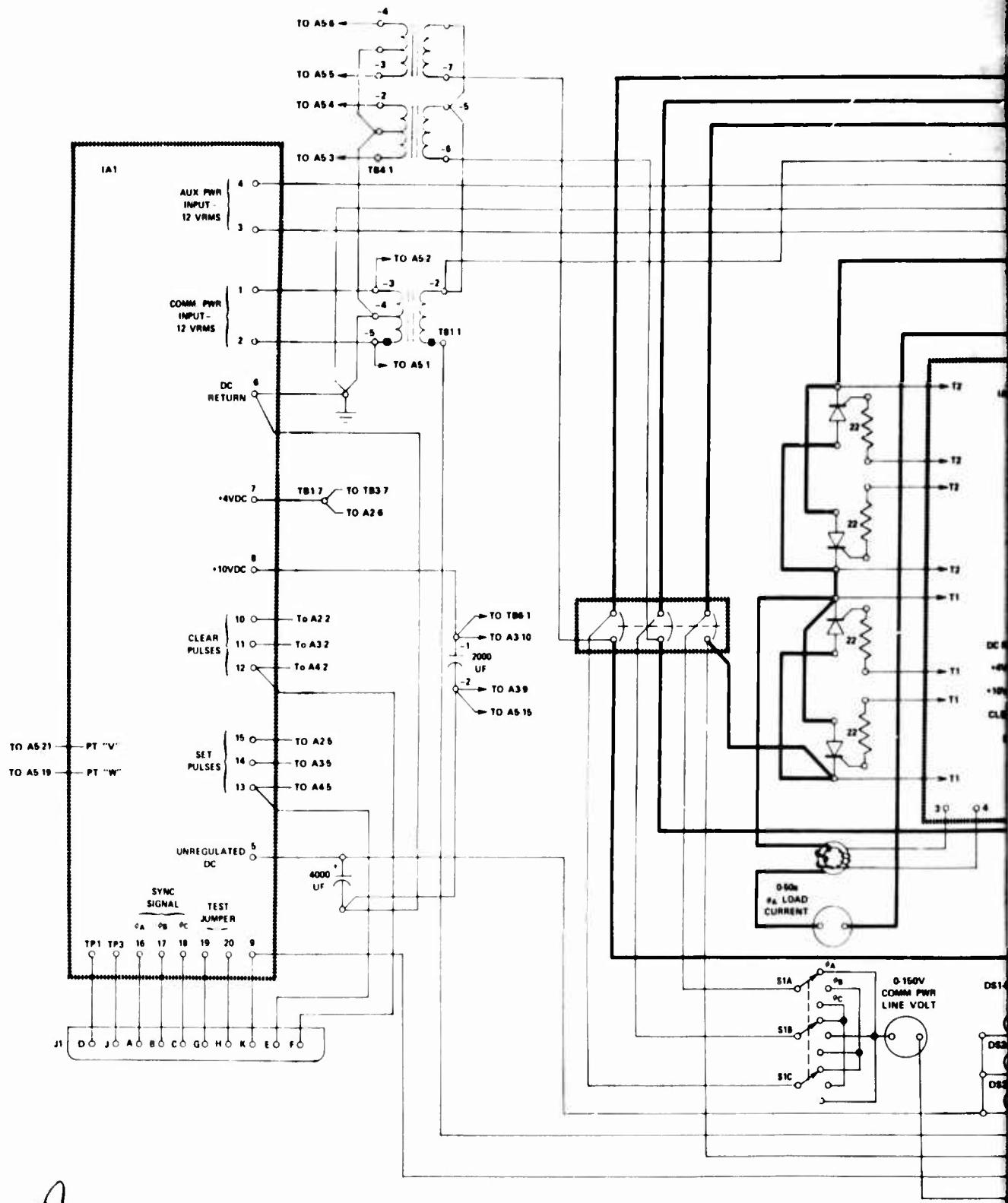


Figure 4. Block diagram of the switching system.



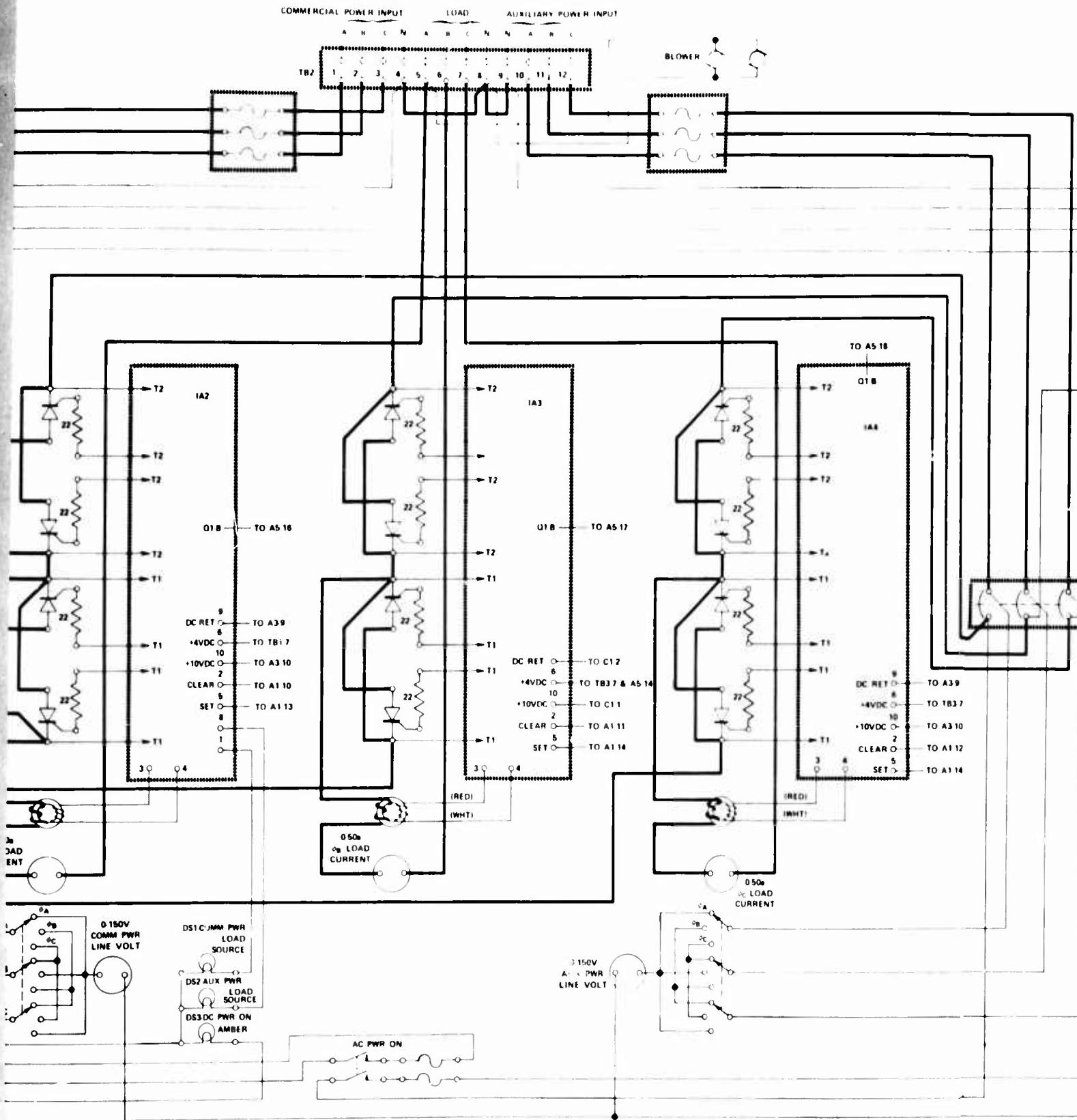
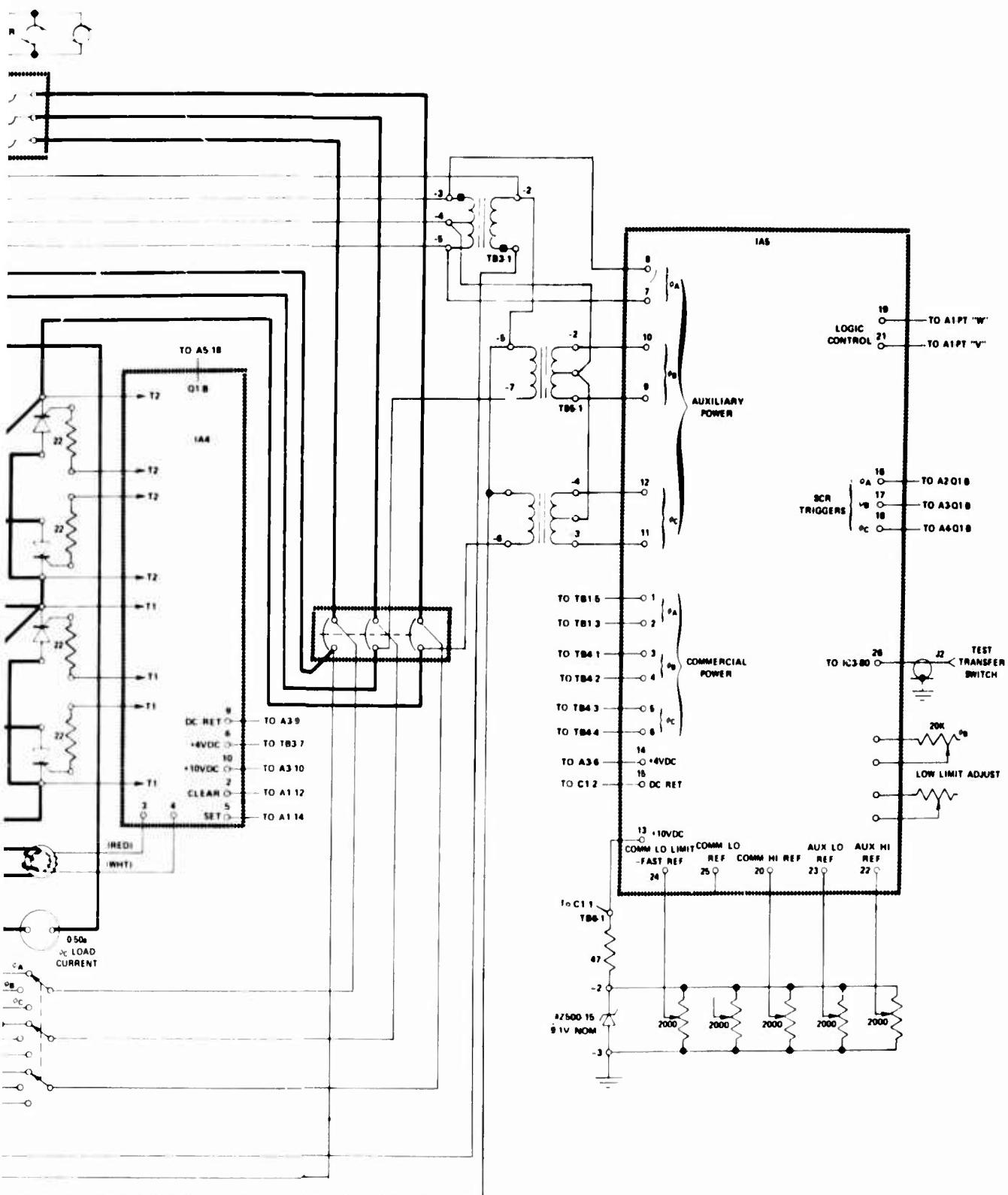


Figure 5. Basic circuit diagram of the switching system.

B



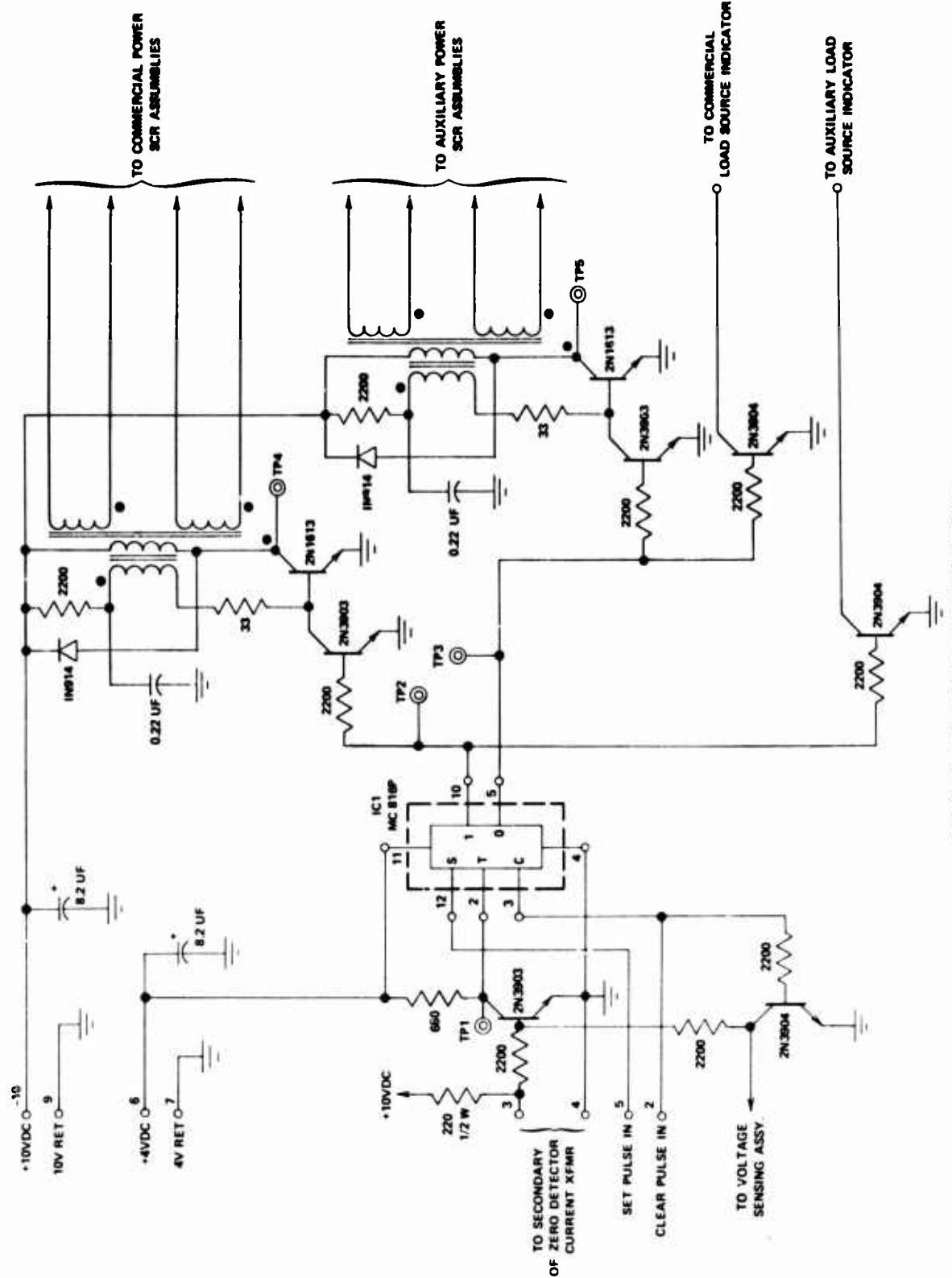


Figure 6. Circuit diagram of SCR trigger.

Voltage-Sensing Circuitry

Basically, the voltage-sensing circuits compare the 3-phase full wave rectified and filtered voltage of the commercial power source to two adjustable DC levels. When the rectified voltage exceeds or falls below the high DC level, the sensing circuitry commands transfer of load to the auxiliary power source. The load is transferred from the commercial to the auxiliary power source almost instantaneously only when the comparators indicate that the auxiliary voltages exceed the commercial voltages. Under all other conditions, transfer is phase sequential. Figure 7 shows the block diagram and Figure 8 the circuit diagram of the voltage-sensing logic circuitry.

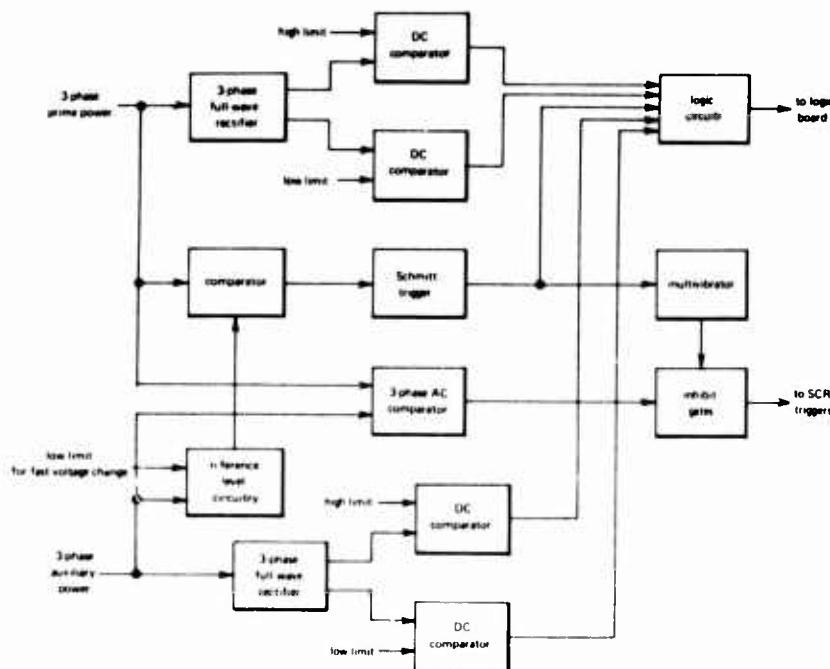


Figure 7. Block diagram of the voltage-sensing circuitry.

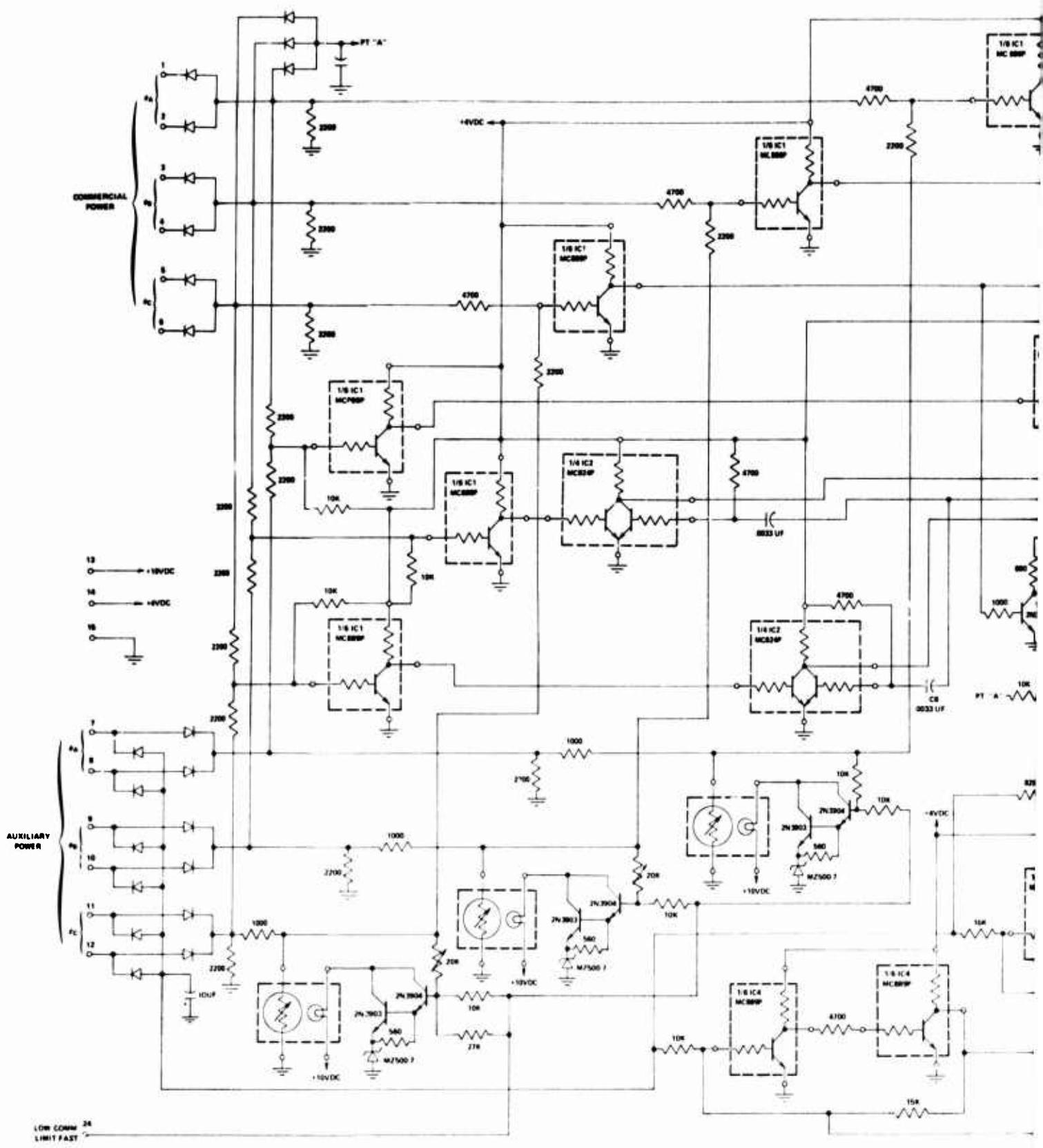
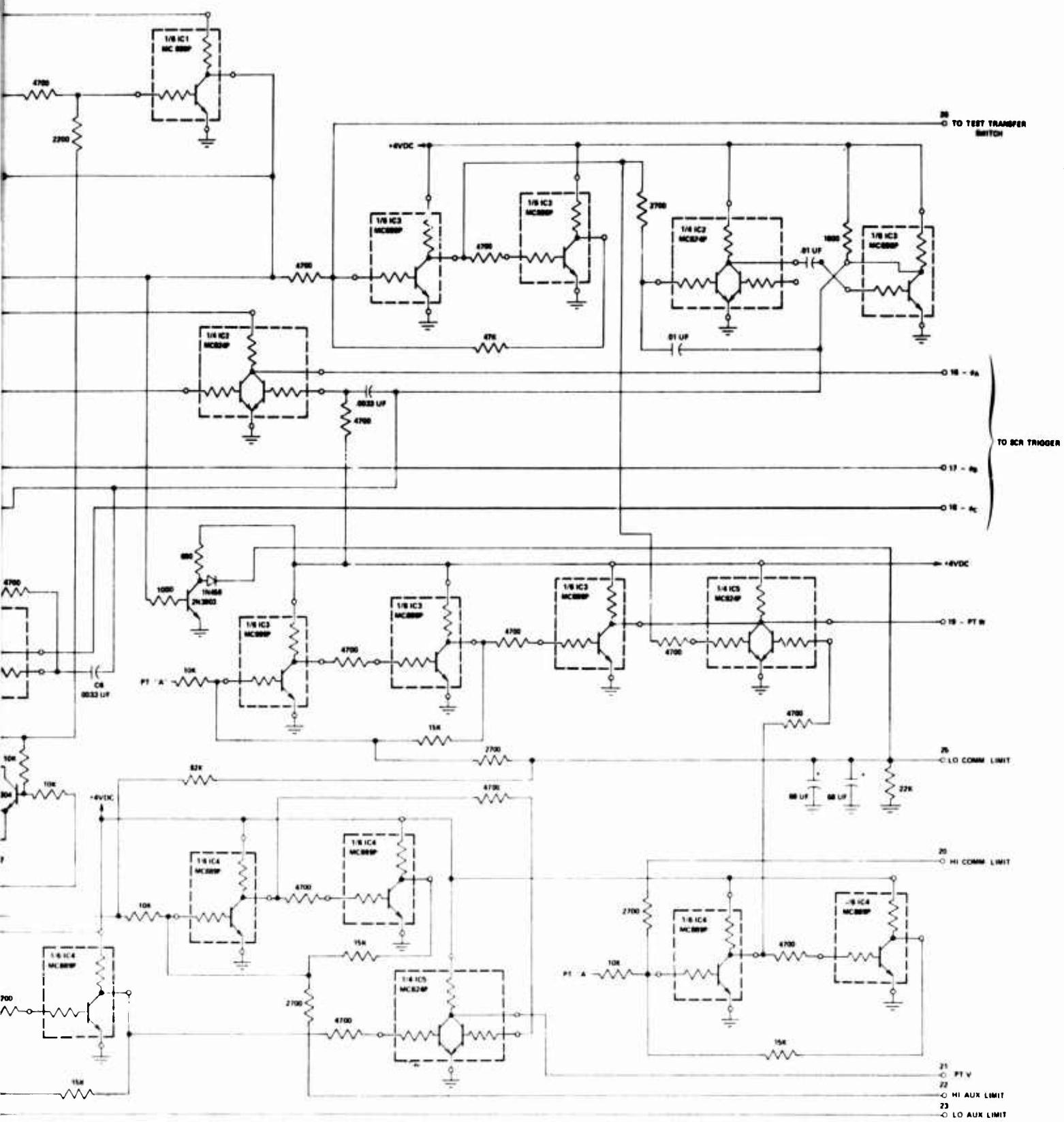


Figure 8. Circuit diagram of the voltage

A



Circuit diagram of the voltage-sensing circuitry.

11

B

Zero Detectors. As described before, to turn off an SCR it is necessary to wait until the load current is zero. In order to avoid the possibility of heavy interpower supply currents, one pair of SCRs must turn off at the same time the other pair is turning on. To accomplish this, current zero-crossing-detector circuitry, shown in Figure 9, is used. Zero-detector transformers sense the instant that the load current becomes zero and generate a trigger voltage which flips the JK multivibrator if the rest of the logic circuitry indicates the need for a power transfer.

Buffer Blocking Oscillators. Buffer blocking oscillator circuitry, keyed on or off by the logic circuitry, is used to control the SCR gates. They generate 10,000 pulses per second, 10 μ sec wide. These oscillators are used in pairs, one being controlled by one state of the flip-flop circuit, while the other is being controlled by the second state.

Flip-Flop Circuit. Figure 10 is a diagram of one of the three triggered flip-flops. Each flip-flop is basically a conventional bistable multivibrator. In the absence of a trigger pulse on the T input, inputs to either the S or C terminals will have no effect on the state of the outputs 1 and 0. The states allowed by the logic circuitry are (1) both S and C are high, (2) S is low and C is high, (3) C is low and S is high. If both S and C are high, no change of state will take place when a trigger is applied. If S is in the low state, the 1 output will either remain on or turn on when the next trigger pulse appears. The 0 output will either turn off or remain off under this condition. If C input is low, then the 0 output will turn on if it is off or remain on if it is on when triggered.

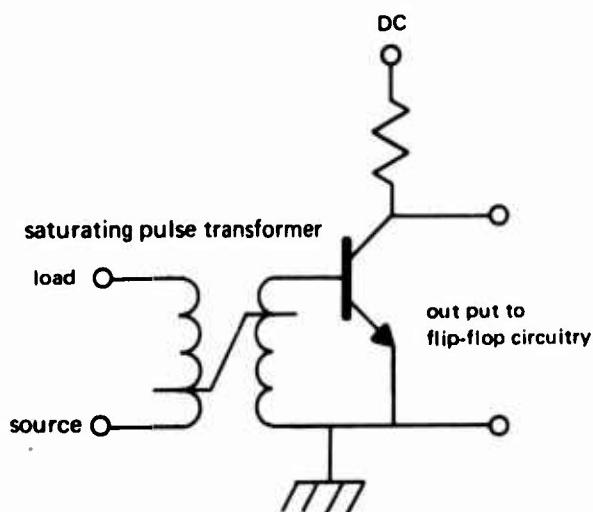


Figure 9. Current zero-crossing-detector circuitry.

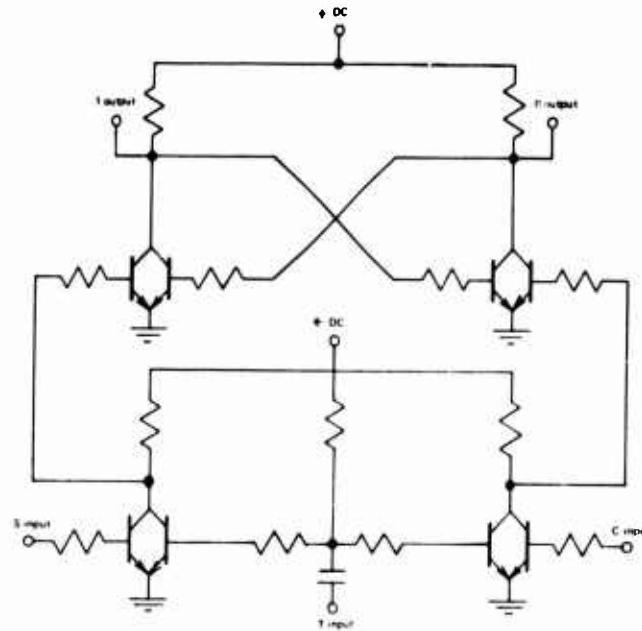


Figure 10. Circuit diagram of the JK flip-flop.

Synchronization Detectors. Synchronization of the two power sources is detected by comparing samples of the phase A voltages from the commercial and auxiliary power supplies in a two-transistor gate. When the two sources are synchronized, the gate output drops sharply to zero.

Frequency-Sensing Circuitry

The frequency-sensing circuitry consists basically of a limiter, a discriminator, and a threshold detector. When the frequency of the commercial source is outside the limits, the output voltage of the sensing circuitry is high (3 volts), while it is less than 1 volt when the frequency is within limits. These high and low outputs command the transfer from one source to the other. Figure 11 shows the frequency-sensing circuitry and the power supply assembly.

Frequency-controlled synchronizing triggers for the auxiliary power source are provided by the synchronization generator. This generator contains an oscillator which, when free running, generates 3-phase triggers at a nominal 60 Hertz and when phase locked to the commercial power source follows its frequency.

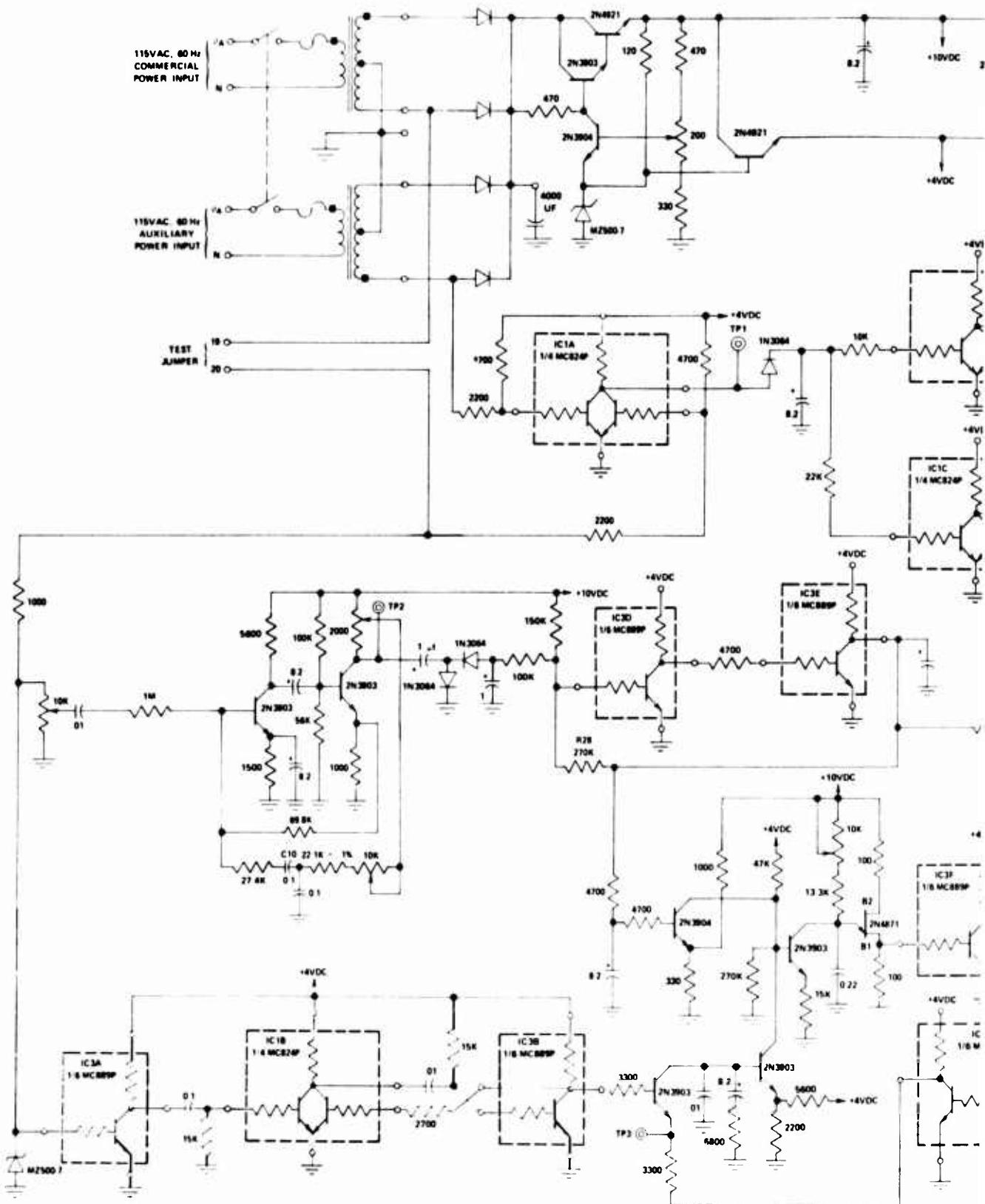
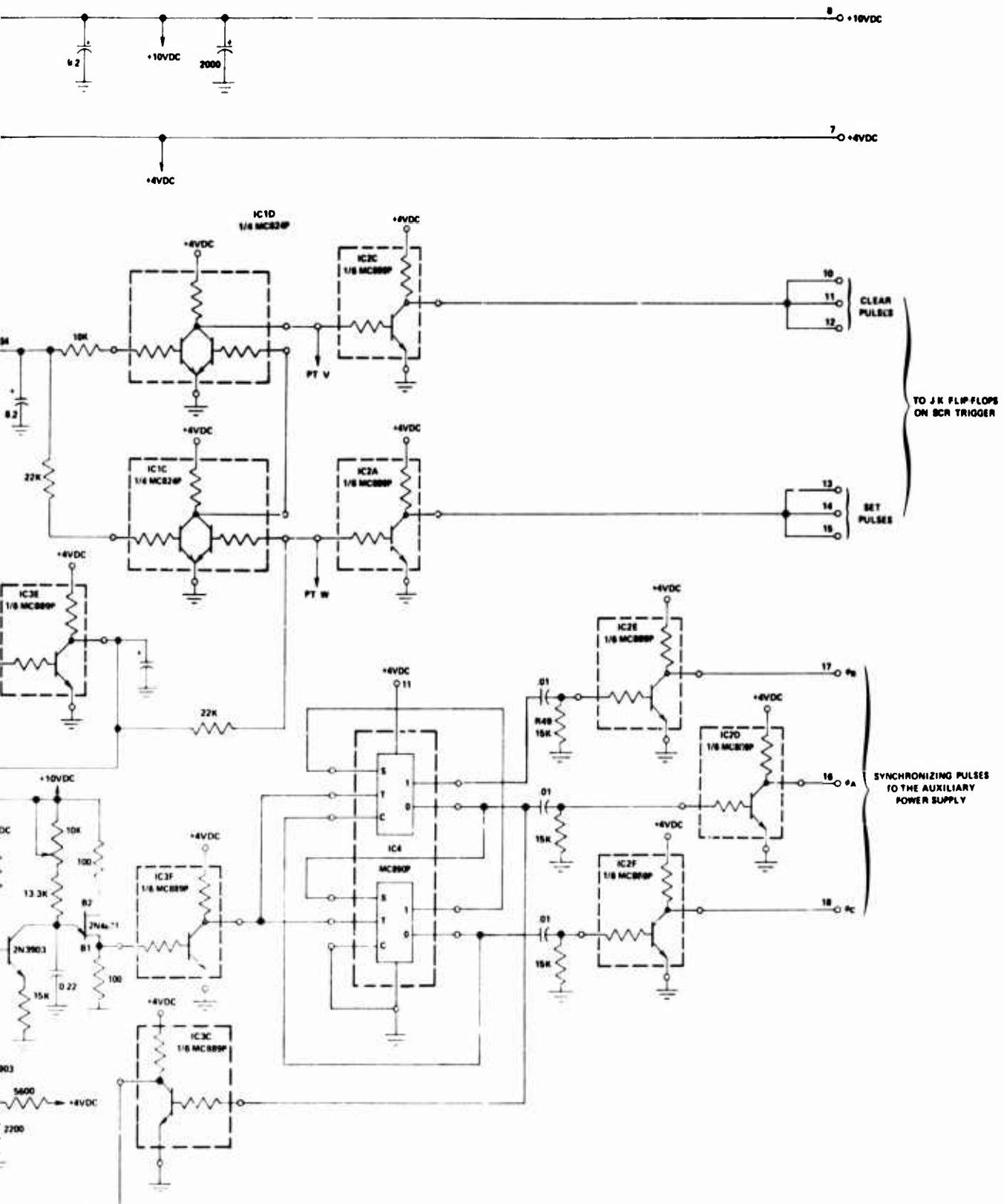


Figure 11. Frequency-sensing circuitry and p



ancy-sensing circuitry and power supply assembly.

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EVALUATION OF PROPOSED SYSTEM

To demonstrate the operation of the switching system and its performance in the laboratory, the system was connected as shown in Figure 12. Both commercial and auxiliary power inputs came from the same source. They reached the load, however, through different sets of SCR switches and through different circuit breakers. Each phase of the 3-phase commercial source was varied by a separate auto transformer so that the performance of the switch to both voltage variations and outages could be demonstrated.

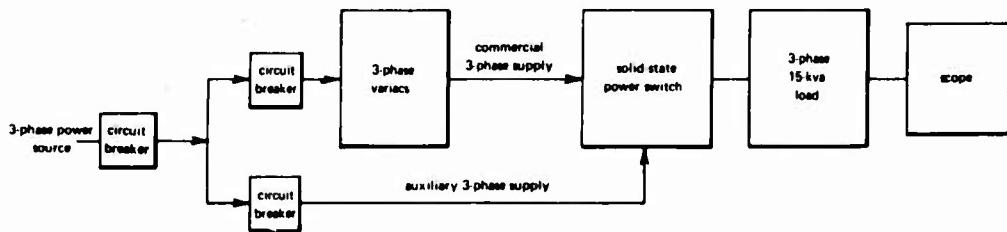


Figure 12. Switching system tests circuit.

Performance Under Variable Load Conditions

Under a no-load condition the switch did not flip from commercial to auxiliary when the commercial source suddenly failed. This transfer, however, was possible when the voltage of the commercial source took a second or more to disappear. Such behavior is due to the finite response time of the selective circuits. The need for transfer under a no-load condition, however, is highly unlikely.

With load variations, including power level and power factor changes, the system was capable of transferring loads up to 15 kva. The load current variation does not appear to have any effect on the switching system performance.

Commercial Source Voltage Variations and Outages

As most critical equipment functions properly within a 10% variation of supply voltages, the voltage limits in the switching system were adjusted so that transfer would not take place unless the commercial voltage is below 105 rms volts or above 130 rms volts. Table 1 is a typical example of the performance of the switching system.

Table 1. Response of Switching System to Voltage Variations and Outages

Voltage Variations and Outages	Commercial			Auxiliary Source			State of Load
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	
Slow voltage changes (undervoltage)	120	120	120	on	120	120	off
	106-103	120	120	undecided*	120	120	undecided*
	120	120	120	off	120	120	on
Fast voltage changes (undervoltage)	104	120	120	undecided*	120	120	undecided*
	105-120	120	120	on	120	120	off
	120	120	120	off	120	120	on
Voltage outage	120-102	120	120	off	120	120	off
	102-120	120	120	on	120	120	on
	120	120	120	off	120	120	off
Slow and fast voltage changes (overvoltage)	120-0	120	120	on	120	120	on
	0-120	120-0	120-0	off	120	120	on
	0-120	0-120	0-120	on	120	120	off
Slow and fast voltage changes (overvoltage)	120-130	120	120	off	120	120	on
	130-120	120	120	on	120	120	off

* Continuous alternate switching between the commercial and auxiliary power sources.

For gradual changes of the commercial voltages and voltages near the threshold switchover value, 105 volts, the system logic caused continuous alternate switching between the two power sources. Figures 13, 14, and 15 show the load waveforms during the transfer to the auxiliary source as a result of voltage drop, overvoltage, and voltage outage, respectively.

Performance During Power Interruptions

The system was connected as shown in Figure 16. The commercial power source was interrupted for various periods of time, and the load voltage waveform was recorded.

Figures 17 through 20 show load voltage waveforms for 1/2, 1, 2, and 5 cycles of interruption, respectively. It is seen from these figures that the switching system was able to transfer the load to the auxiliary source without much load waveform interruption.

Total Switchover Time

The total switchover time was estimated from voltage waveforms obtained on a storage oscilloscope. Figure 21 shows the voltage load waveform for a resistive load, where the switching time from commercial to auxiliary is seen to be about 400 μ sec. Switching inductive loads with a power factor of 0.8, however, takes 800 μ sec (see Figure 22). The delay in the inductive load appears to be due to the SCR behavior when both the voltage and the current are not in phase (see the Appendix).

FINDING

The power source transfer time is typically 400 μ sec for loads with a unity power factor and 800 μ sec for loads with a 0.8 power factor.

CONCLUSION

A conditioned power system employing solid-state power switching is an economical method for providing suitable quality electrical power to electronic systems and equipment which are not adversely affected by a power interruption of a few milliseconds duration.

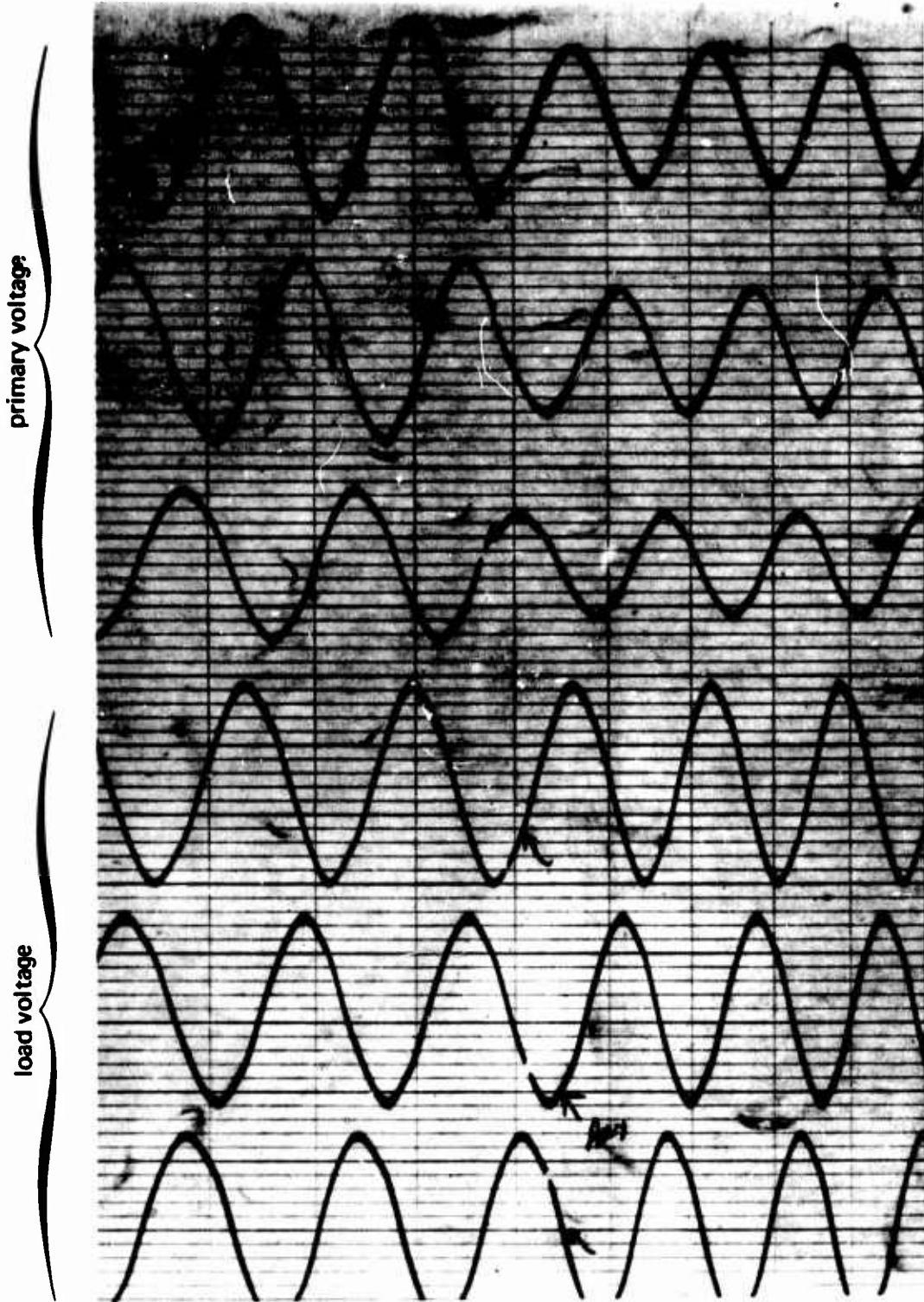


Figure 13. Voltage load waveform during load transfer to the auxiliary power source due to primary source voltage drop.

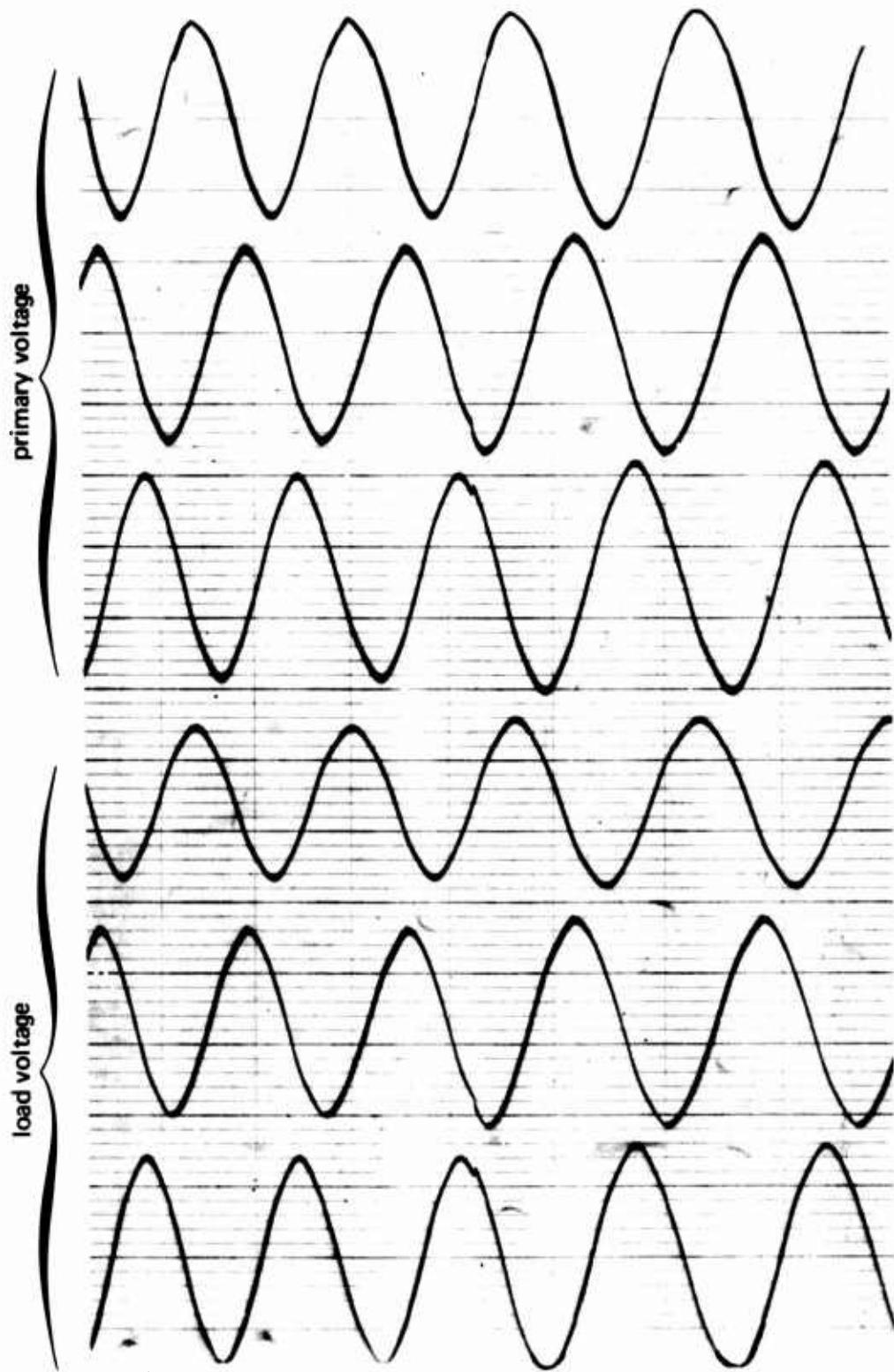


Figure 14. Voltage load waveform during load transfer to the auxiliary power source due to primary source overvoltage.

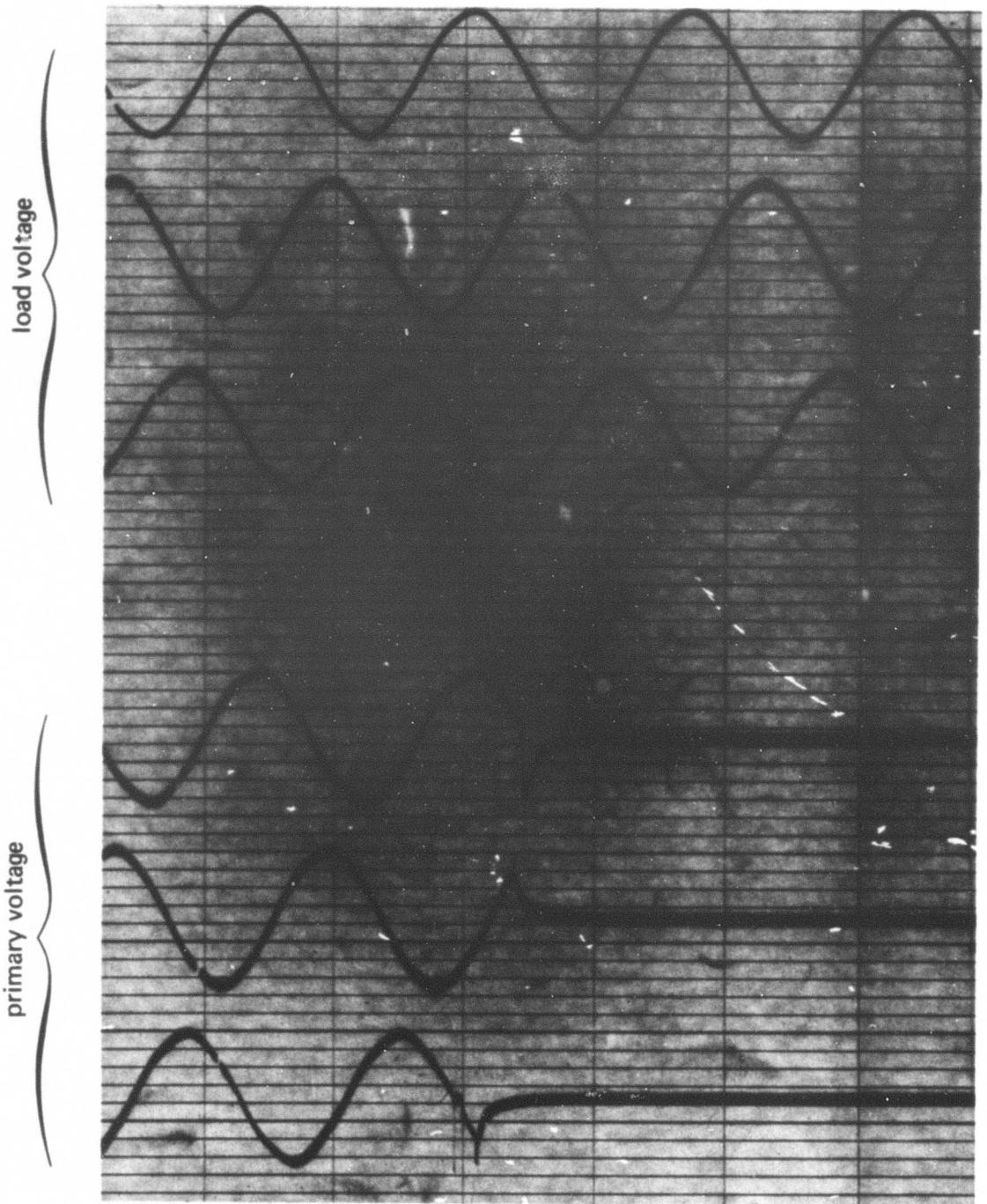


Figure 15. Voltage load waveform during load transfer to the auxiliary power source due to primary source voltage outage.

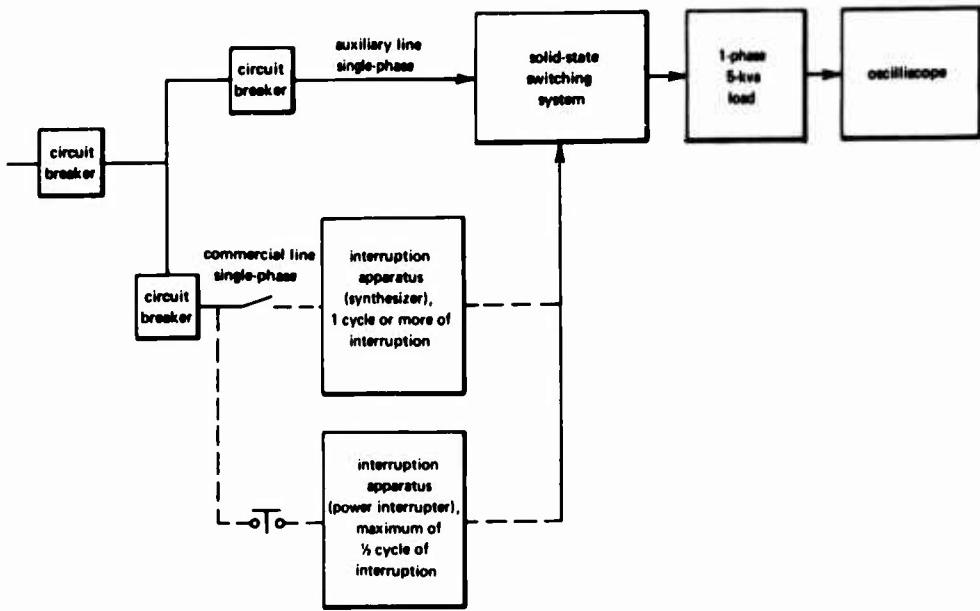
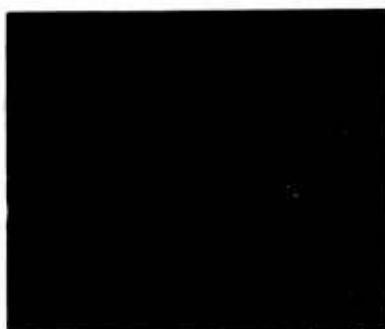


Figure 16. Circuit diagram for testing power interruption performance.



Horizontal: 5 msec/div
 Vertical: 100 volt/div

Figure 17. Voltage load waveform with 1/2 cycle primary source power interruption.

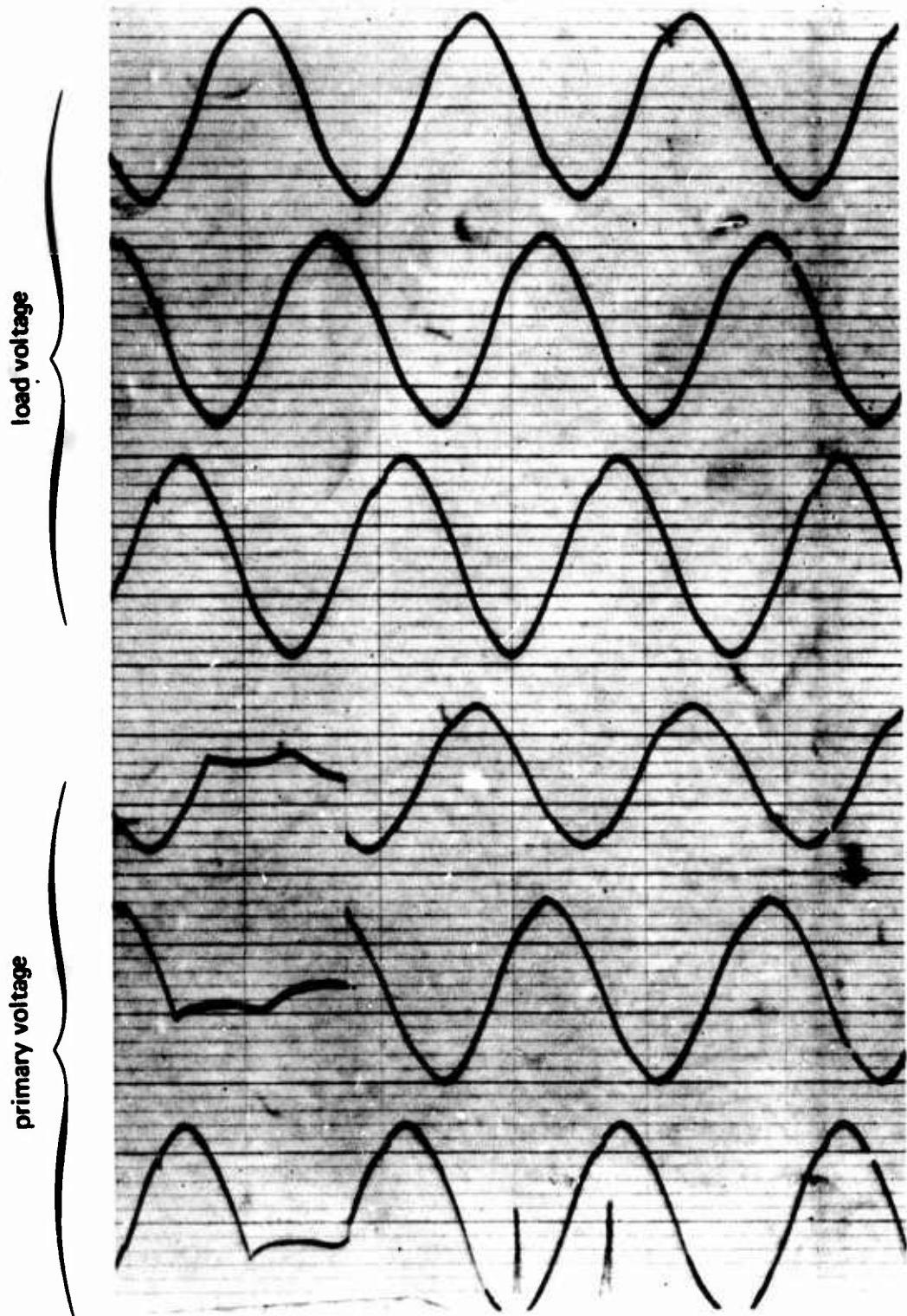


Figure 18. Voltage load waveform with 1 cycle primary source power interruption.

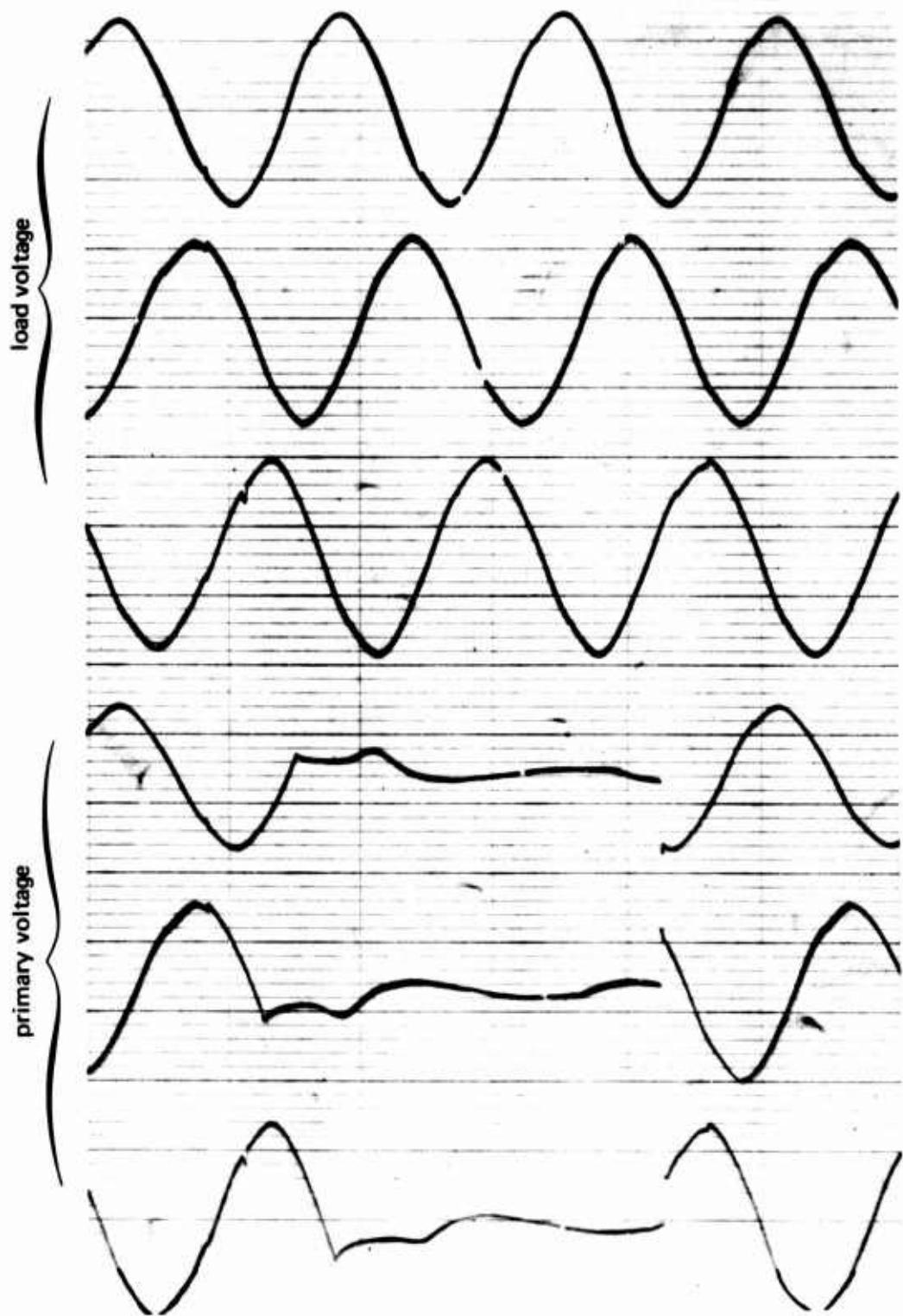


Figure 19. Voltage load waveform with 2 cycles primary source power interruption.

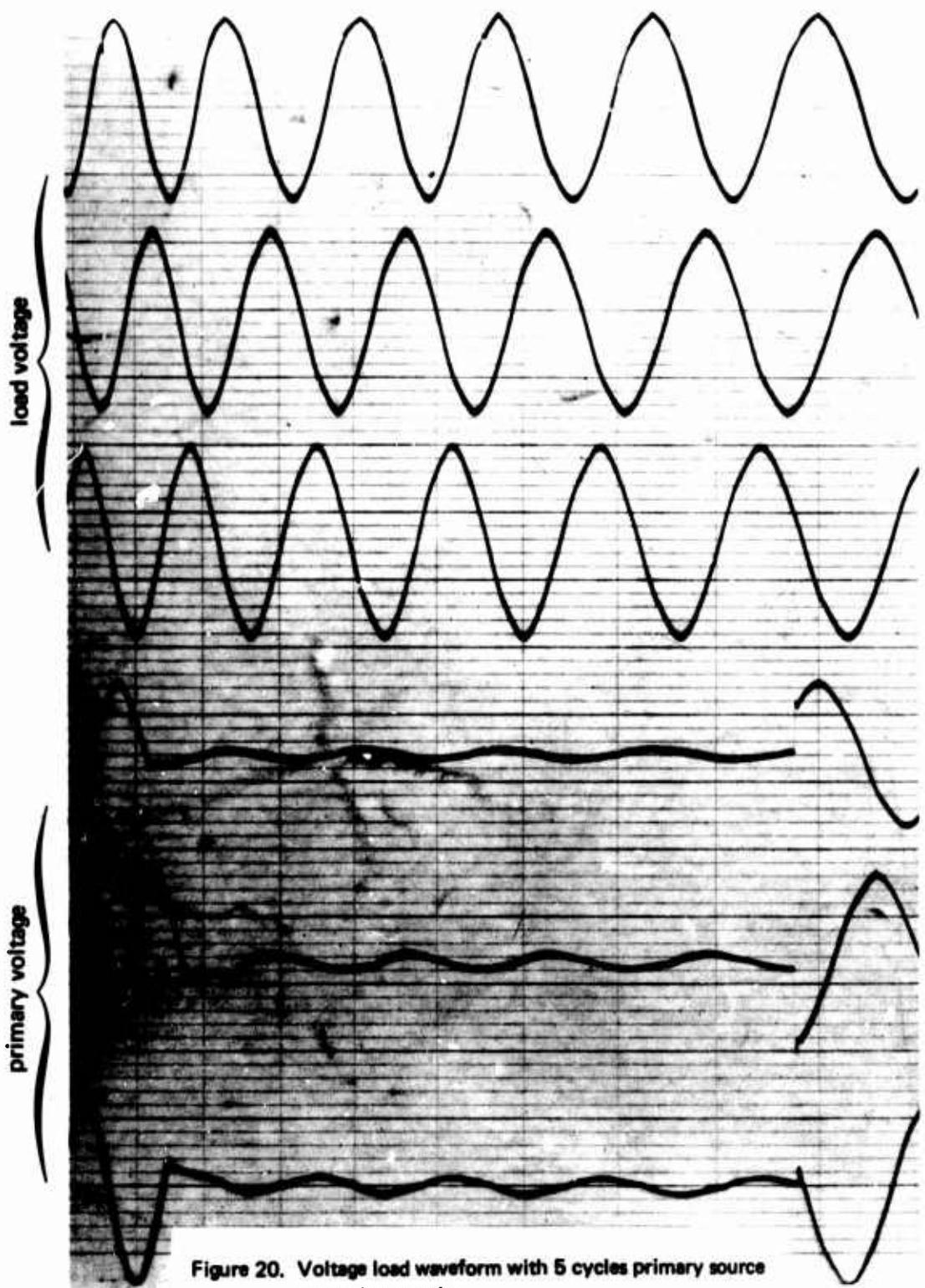
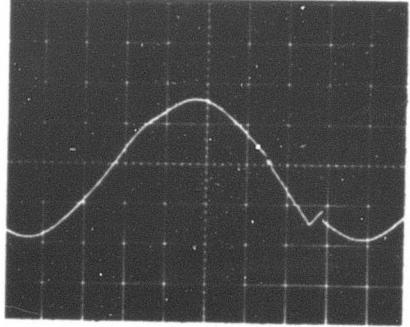


Figure 20. Voltage load waveform with 5 cycles primary source power interruption.



Horizontal: 2 msec/div
Vertical: 100 volt/div

Figure 21. Resistive load voltage waveform during transfer from primary source to auxiliary source.



Horizontal: 2 msec/div
Vertical: 100 volt/div

Figure 22. Inductive load voltage waveform during transfer from primary source to auxiliary source.

Appendix

THEORY OF THE OPERATION OF AN SCR

The operation of the solid-state switching system described depends on the electrical characteristics and limitations of the SCRs. Figures 23 and 24 show the basic voltage-current relationship of a single SCR and a set of two back-to-back SCRs.

It is seen from Figure 23 that if an AC voltage with moderate amplitude, say not exceeding the range between A and B, is applied negligible current will flow through the device; in this case, the device will act as an open switch to both positive and negative halves of the AC cycle. If the amplitude of voltage is increased beyond point B to point C or higher, transistor action will take place and move the operating point to the region A' B', where the device will act as a closed switch for the positive half cycle.

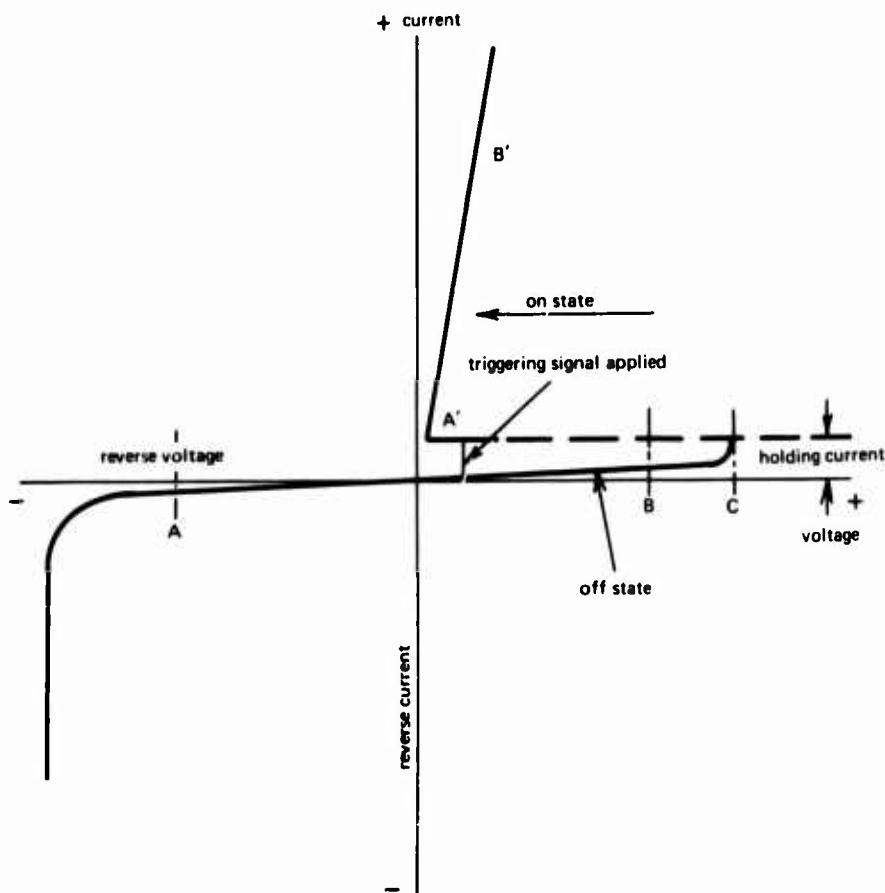


Figure 23. Principal voltage-current characteristics of an SCR.

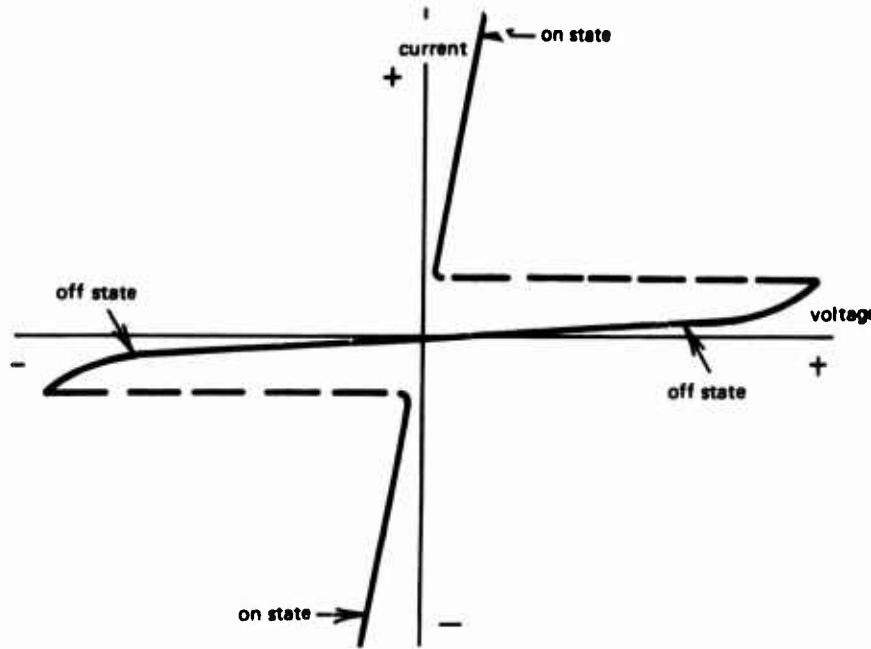


Figure 24. Principal voltage-current characteristics of two back-to-back-connected SCRs.

SCRs, however, can be made to operate in the off and on states without increasing the applied voltage beyond the region AB. This is normally done by the application of a triggering signal. This signal will switch operation to the A' B' region for any forward bias exceeding about 0.75 volt but not exceeding the potential at point C. The transition time depends on the regenerative action of the circuit so that once the avalanche of carriers is initiated the switch closes in a very brief time (about 2 μ sec). The switch will be closed as long as there is a sufficient (normally small) amount of holding current flowing through it. The switch will turn off only if the current passing through it drops below the holding value, and then the device will switch to the non-conducting state. The turning-off time depends on the recombination of the carriers and is usually about 25 μ sec.

Two similar SCRs connected back-to-back are used to switch both halves of the AC cycle off and on. In this case, the full waveform can be turned off and on by triggering both gates of the SCRs simultaneously at the proper time.

From the above discussion, it is clear that while an SCR can be turned on at any time, it is necessary to wait until the current goes to zero in order to turn it off.

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13. ABSTRACT The reliable operation of critical electronic equipment employed at naval shore installations and other Department of Defense installations requires conditioned electrical power. A conditioned power system is proposed which is potentially one-fifth as costly as power systems employing solid-state or rotary uninterruptible power supplies. The proposed conditioned power system employs high-speed, solid-state power source switching. A 15-kva, 208-volt, 60-Hertz, 3-phase demonstration model of the proposed system has been developed and laboratory evaluated. This model accomplishes power source transfer in 800 μsec. Because of its fast switching speed between two power sources, the system is potentially capable of conditioning power economically for many critical loads.		

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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